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DETERMINATION OF THE NONUNIFORMITY OF VENTILATION BY THE HELIUM MIXING TIME IN THE LUNG – SPIROGRAPH SYSTEM

L. A. Sidorenko

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Dependence of the helium mixing time in the lung–spirograph system of factors influencing its value was analyzed. In the case of uniform ventilation of the lungs graphs were plotted by means of which the "ideal" mixing time was determined. It is suggested that nonuniformity of lung ventilation be judged by the amount by which the mixing time obtained during investigation of the patient's respiration exceeds the "ideal" time found for the same patient from the graph.
KEY WORDS: ventilation of the lungs; helium method; residual lung volume.

The helium method is usually used to determine the residual lung volume. In the course of this investigation data are obtained on the time during which almost uniform mixing of helium takes place in the lung–spirograph system. Attempts are often made to judge the nonuniformity of the lung ventilation by the mixing time without allowing for how it depends on other factors: the longer the mixing time, the greater the nonuniformity of ventilation. However, the mixing time depends not only on the nonuniformity of lung ventilation, but also on indices such as the minute alveolar ventilation, the functional reserve capacity, the volume of the spirograph and initial helium concentration in it, and also on the experimental conditions. The problem thus arises of allowing for the dependence of the helium mixing time in the system on the factors listed above, so that the nonuniformity of alveolar ventilation can be estimated on the basis of this parameter.

The mixing time which the patient should have if his lungs were uniformly ventilated may be called the "ideal" mixing time. Clearly, the greater the nonuniformity of the patient's pulmonary ventilation, the more the mixing time will exceed the "ideal" value found for the same patient, other conditions being the same.

An equation was obtained for determining the "ideal" mixing time t:

$$t = \left(V_1 V_2 \ln \frac{c_0 u \Delta t}{\Delta c V_1}\right) : [u (V_1 + V_2)], \tag{1}$$

where V_1 is the volume of the spirograph (the bell and dead space of the instrument) before the beginning of the test; c_0 the initial fractional helium concentration in the spirograph; V_2 the functional residual capacity (FRC) of the patient's lungs determined during the investigation; u the minute alveolar ventilation (MAV); Δt and Δc parameters characterizing the conditions for stopping the investigation.

The time of stopping the investigation can be chosen in different ways by different investigators for this gives different interpretations of the degree of uniformity of mixing. In the general sense the conditions of stopping the investigation can be defined as follows: The investigation is stopped when changes in the helium concentration in the spirograph decrease to a certain small value Δc at time intervals Δt chosen for the observation. Since the aim of the investigation is to compare results obtained in practice with those calculated theoretically, it is important that during theoretical calculation the values of Δt and Δc be chosen to be the same as the conditions of stopping the investigation during experimental determination of the mixing time.

Department of Functional Diagnosis of the Respiratory Organs, Central Hospital, No. 4 Main Administrative Board, Ministry of Health of the RSFSR, Moscow. (Presented by Academician V. N. Chernigovskii.) Translated from Byulleten' Éksperimental'noi Biologii i Meditsiny, Vol. 84, No. 11, pp. 631-632, November, 1977.

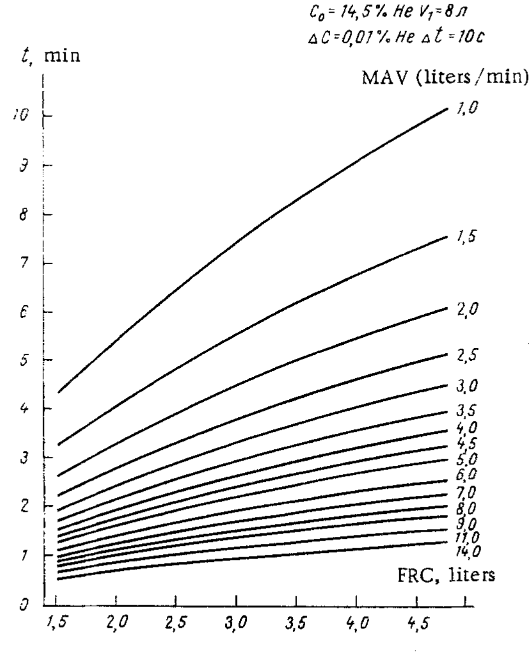

Fig. 1. Determination of "ideal" helium mixing time in the lung–spirograph system. The "ideal" mixing time (ordinate) is found from the value of the functional residual capacity (abscissa) and minute alveolar ventilation (the vertical column of numbers on the right). The parameters for which these graphs were plotted are indicated in the top right-hand corner.

Equation (1) was obtained as follows. Changes in the helium concentration in the spirograph after connection to the patient system can be represented by the following differential equation:

$$V_1\,dc_1 = -uc_1\,dt + uc_2\,dt,$$

where c_1 is the helium concentration in the spirograph; c_2 the same in the lungs; dc_1 the change in the helium concentration in the spirograph during time dt; uc_2dt the quantity of helium entering the spirograph; uc_1dt the quantity of helium leaving the spirograph during time dt.

Considering that $c_1V_1 + c_2V_2 = c_0V_1$, we obtain

$$\frac{dc_1}{dt} = -\left(\frac{u}{V_1} + \frac{u}{V_2}\right)c_1 + \frac{u}{V_2}\,c_0. \tag{2}$$

Equation (2) can be written in the simplified form

$$\frac{dc_1}{dt} = ac_1 + b, \tag{3}$$

where $a = \frac{-u(V_1+V_2)}{V_1V_2}$ and $b = \frac{uc_0}{V_2}$. Substituting in Eq. (3) the variables $y = ac_1 + b$, we obtain the differential equation $dy/y = a\,dt$, which is easily solved. It solution has the form $y = k \exp(at)$. When $t = 0$ $k = uc_0/V_1$ considering the above arguments, we obtain

$$y = -\frac{uc_0}{V_1}\exp\left(-u\frac{V_1+V_2}{V_1V_2}\,t\right).$$

Reverting to the original variable, we obtain a relationship between the helium concentration in the spirograph c_1 and time and the other variables:

$$c_1 = \frac{c_0V_1}{V_1+V_2} + \frac{c_0V_2}{V_1+V_2}\exp\left(-u\frac{V_1+V_2}{V_1V_2}\,t\right).$$

Considering that the investigation is stopped when the change in the helium concentration in the spirograph during time Δt falls to Δc, it is easy to obtain the Eq. (1) for calculating the "ideal" gas mixing time in the lung–spirograph system.

Repeated calculations of the "ideal" mixing time by Eq. (1) in everyday practice would be a difficult task. Graphs simplifying this process were accordingly plotted. The dependence of the "ideal" time on the value of

FRC for different values of MAV are shown in Fig. 1, for Eq. (1) reduces to the dependence of t on these two indices. Graphs were plotted from the numerical data obtained by computer using the simplest program for calculating t by Eq. (1) for different values of V_2 and u. The remaining parameters in this case were given values corresponding to those obtained experimentally. The volume of the spirograph V_1 and also the initial helium concentration in it c_0 are almost constant under the comparatively uniform conditions of the investigation and they can be taken as known. FRC (V_2) is determined for each patient in the course of the investigation. MAV (u) is found from the spirographic data. For its determination it is also essential to know the anatomical dead space (ADS), and this can be determined by additional experimental investigations or, if the apparatus required for determination of ADS is not available, the known norms can be used [2, 3]. The values of Δt and Δc, together with the remaining initial data are indicated on Fig. 1. Others more acceptable for other investigators can also be chosen for them. If the initial data differ from those for which the graphs were plotted in this paper, new graphs can be drawn to determine the "ideal" mixing time in accordance with Eq. (1).

Reports of the detection of disturbances of ventilation on the basis of the helium method have been published [1, 4-7]. However, strict, scientifically based "norms" of an index such as the mixing time were not given in these papers. The results of the present investigation enable a "norm" of the helium mixing time, namely the "ideal" mixing time, to be found for each patient and, depending on by how much the true mixing time exceeds the "ideal" time, the nonuniformity of pulmonary ventilation can be judged. The reason for this excess is disturbances of ventilation connected with pathological changes in the respiratory apparatus such as disturbances of bronchial patency, emphysema, compensatory changes in the blood flow, and so on.

Hence, as a result of these calculations and constructions, it was possible to draw valid conclusions regarding the presence or absence of nonuniformity of pulmonary ventilation from the helium mixing time in the lung–spirograph system, so that the mixing time itself acquires definite interest in connection with the comprehensive investigation of external respiration.

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